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IAMPIETRO, P. F., J. A. VAUGHAN, R. F. GOLDMAN, M. B. KREIDER, F. MASUCCI AND DAVID E. BASS. *Heat production from shivering*. J. Appl. Physiol. 15(4): 632-634. 1960.—Healthy young men were exposed, nearly nude, for 2 hours or less to various environmental conditions (dry-bulb temperature, 90°–20°F; windspeed, <1, 5, 10 mph). Oxygen consumption was recorded at intervals during exposure. The results show that even under conditions where no visible shivering was observed, there was an increase in heat production. Exposure to very low temperatures (20°F) with low winds did not evoke the largest increases in heat production. The greatest mean heat production (370 Cal/hr.) was associated with the highest windspeed (10 mph), and this value approached the maximum heat production which can be attained by shivering (mean value about 425 Cal/hr.). Thus, increasing the windspeed had a relatively greater impact on heat production than decreasing the dry-bulb temperature. The relationships between heat production and windspeed and heat production and dry-bulb temperature were nonlinear.

THE EFFECTS OF ACUTE COLD EXPOSURE on heat exchanges of nude men have been studied by several workers (1–3). Attention has been given to investigations of heat balances (1), thermal insulation (4), relation between shivering and body temperatures (5, 6), effects of humidity (2, 3), racial differences in physiological responses (7–10), and many others. However, systematic investigations of the role of wind and dry-bulb temperature on shivering heat production are few (1). It is reasonable to expect that shivering, and heat production, would increase with decreasing ambient temperatures and increasing winds. It is also reasonable to expect that there is a maximum rate of heat production from shivering and that this maximum will be reached when all muscles capable of responding to the cold stimulus are responding fully. The purpose of the present study was threefold: 1) to determine the maximum rate of heat production from shivering, 2) to establish those ambient conditions (dry-bulb temperature and windspeed) which evoke the maximum heat production and 3) to determine the rela-

tive effects of windspeed and dry-bulb temperature on heat production.

EXPERIMENTAL DESIGN AND METHODS

From 6 to 16 young men (mean wt. 70.77 kg, mean S.A. 1.82 m²) were exposed nude (except for shorts and, during the more severe exposures, cotton socks) in a constant temperature room to various combinations of dry-bulb temperature (90°–20°F) and windspeed (<1, 5, 10 mph); relative humidity was maintained at 50%. All men were exposed simultaneously to a given set of conditions. Exposure to each environment was limited to 2 hours, but was less than 2 hours for the more severe conditions. During one experiment, two highly motivated subjects remained in the chamber for 120 minutes at a temperature of 20°F, wind <1 mph. Exposure was preceded by 1 hour at a comfortable temperature (control, 80°F, 50% R.H., air movement 20 ft/min.). Subjects reported at 8:00 A.M. in the fasting state. During control and experimental periods the subjects were in a semi-reclining position. Oxygen consumption was measured by collecting expired air in a Tissot spirometer, and analyzing for oxygen with a Beckman oxygen analyzer. Calculations of heat production were made according to Weir (11). Oxygen consumption was measured at 15–30-minute intervals during cold exposure.

The following notation will be used to describe environmental conditions: dry-bulb temperature/windspeed, e.g. 60/5 indicates dry-bulb temperature 60°F, windspeed 5 mph.

RESULTS

Figure 1 shows heat production for all conditions studied. For purposes of clarity, experiments conducted at windspeeds <1, 5 and 10 mph are plotted separately. It is readily apparent that heat production from shivering increases as ambient temperature decreases and as windspeed increases. Although no measure of the amount of shivering, per se was made, figure 1 indicates that in all conditions except 80/<1 and possibly 90/10, some increased muscle activity was present. However, subjective

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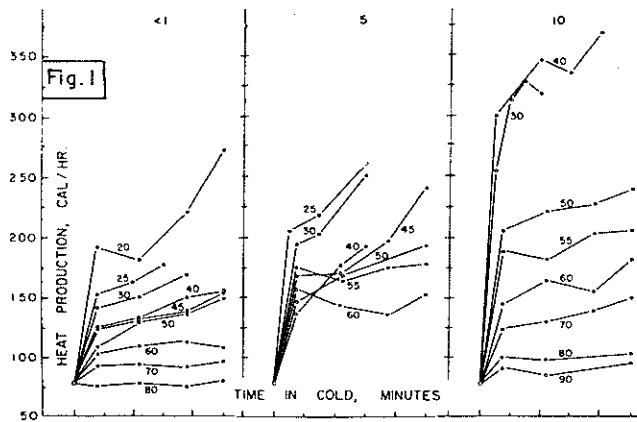


FIG. 1. Heat production from shivering during cold exposure. Numbers at top of figure (<1, 5, 10) refer to wind velocity (mph). Numbers on each curve refer to ambient temperature ($^{\circ}\text{F}$).

evaluation by the investigators indicated that there was no noticeable muscle activity (shivering) in some conditions although these same conditions gave small increases in heat production, e.g. 70/<1, 80/10.

The time course of the increase in heat production varied, both with ambient temperature and windspeed (fig. 1). When dry-bulb temperature was 60 $^{\circ}\text{F}$ or higher, heat production increased rapidly during the first 15–20 minutes of exposure and then leveled off. When ambient temperature was lower than 60 $^{\circ}\text{F}$ heat production continued to increase at a slower rate after the first 20 minutes of exposure, and this increase was essentially linear with time. In all conditions, 50–100% of the increase in heat production was accomplished during the first 20 minutes of exposure. The effect of increasing windspeed at a given ambient temperature was to increase heat production. Thus, heat production after 60 minutes exposure at 40/<1 was about 145 Cal/hr., at 40/5, 190 Cal/hr. and at 40/10, 335 Cal/hr. Figures 1 and 2 show that decreasing the ambient temperature when wind was <1 mph caused relatively small increases in heat production, while decreasing the ambient temperature when wind was 10 mph caused large increases in heat production. It is evident in figure 2 that there is no simple relationship between heat production, dry-bulb temperature and windspeed.

The greatest individual heat production from shivering that we have measured was 442 Cal/hr. after 30 minutes exposure to 30/10; we have also measured several heat productions above 400 Cal/hr. Figure 1 does not give a complete picture of heat production at 30/10 since some men did not complete more than 30 minutes of exposure. It is quite probable that heat production would have been greater with more time in the cold and that the

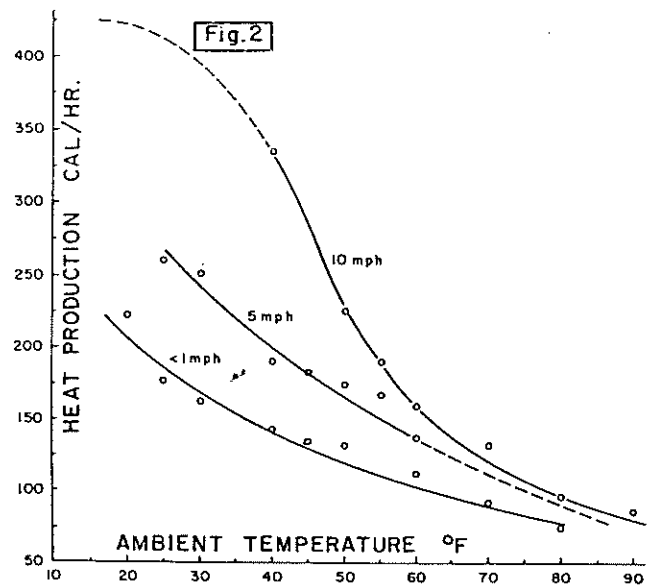


FIG. 2. Heat production of nearly nude men at 60 min. of exposure vs. ambient temperature. Numbers on each curve refer to wind velocity (mph). Dashed portions of upper and middle curves are extrapolations of the data.

final average level reached would have approached 400 Cal/hr. Based on the results of exposure to 30/10 and 40/10 we believe that the maximum heat production from shivering probably does not exceed 400–425 Cal/hr., or about 5 times the resting rate (80 Cal/hr.). We have extrapolated the 10-mph curve (dotted portion) to indicate this maximum (425 Cal/hr.).

DISCUSSION

Physiological tolerance to cold can be regarded as a function of a working balance between input and output

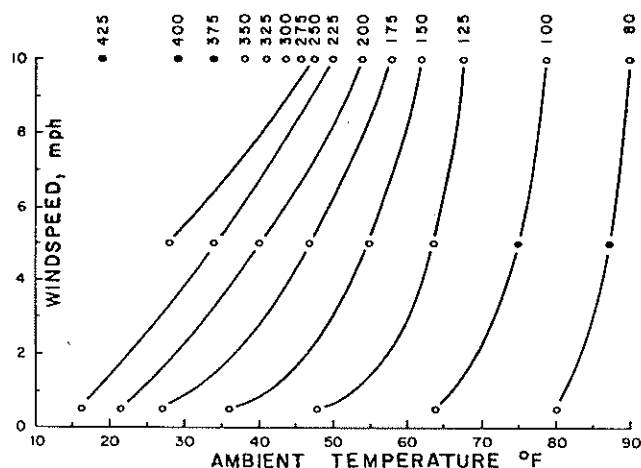


FIG. 3. Heat production from shivering as a function of wind-speed and ambient temperature. Numbers at top of each curve represent heat production to be expected during exposure to any combination of conditions which fall on that curve. Open circles, values selected within the range of conditions actually studied; closed circles, estimated values outside the range of conditions studied.

of heat. Output of heat is dependent on surface area and the gradient between surface temperature and surrounding temperatures. Input of heat, in the resting man in the cold, can only be augmented by shivering. In this investigation we have attempted to describe changes in heat input which occur when nearly nude men are exposed to diverse environmental situations. Environmental factors we studied were windspeed and dry-bulb temperature. The results show clearly that heat production is influenced both by dry-bulb temperature and windspeed. This is not in agreement with the findings of Adolph and Molnar (1) who conclude that wind velocities had no significant correlation with oxygen consumption. However, the design of their experiments did not lend itself readily to an assessment of the effect of wind velocities, per se. Their experiments were conducted out of doors on a rooftop and thus were subject to winds which might have varied markedly during a single exposure. Another factor to be considered is that our studies were conducted in a wind tunnel and air flow was probably nearly laminar whereas air flow in the studies of Adolph and Molnar were more turbulent. Figure 2 indicates that the highest rate of heat production was reached when wind was 10 mph. During exposure to the same dry-bulb temperature, but with wind <1 mph, heat production was about one third as great. We also did not find a linear relationship between heat production and dry-bulb temperature, as did Adolph and Molnar. When wind was <1 mph, heat production over the range 80° – 30° F increased almost linearly, but this near-linearity was lost when dry-bulb temperature was lower than 30° F. It is also seen that there is no linearity between heat production and dry-bulb temperature when wind was 5 or 10 mph. Figure 3, which was constructed from the data in figure 2, shows this nonlinearity well; equal increments in heat production (25 Cal/hr.) are not elicited by equal decrements in dry-bulb temperature at any of the windspeeds studied. Figure 3 allows a rough estimation of heat production for any windspeed up to 10 mph at any ambient temperature down to 40° F, and also allows estimation of heat production at lower ambient temperatures for windspeeds <10 mph.

A striking feature of this work is that heat production during exposure to very low (for nude men) ambient

temperatures was relatively small when windspeeds were low. Two well-motivated men remained in the chamber at $20^{\circ}/<1$ for 2 hours, yet heat production at 100 minutes was considerably less than heat production after 40 minutes exposure to $40^{\circ}/10$. It is likely that maximum heat production from shivering cannot be evoked merely by exposing nude men to low dry-bulb temperatures without also having a wind of at least 10 mph. This may be due to the fact that exposure to a given temperature with minimal wind gives a higher skin temperature than when windspeed is high. The higher skin temperature was probably due to the fact that a static, insulating film of air surrounded the body when windspeed was low, but not when windspeed was high. There is therefore less of a surface stimulus for shivering when windspeed is low. Skin temperatures (to be reported later) recorded after 60 minutes exposure to $20^{\circ}/<1$ were actually higher than skin temperatures recorded after 60 minutes exposure to $40^{\circ}/10$. We are in agreement with Swift (5) and Adolph and Molnar (1) that the maximum heat production from shivering is about five times resting heat production, or about 425 Cal/hr. The quite marked variation in heat production, both inter- and intraindividual, makes this estimation difficult. Another factor to be considered is that all subjects did not exhibit comparable increases in heat production with time in the cold. Some subjects started to shiver immediately and reached peak heat production in a very short time, whereas others required considerable time to reach a peak. There seemed to be no relationship between the time to reach peak heat production and body composition, i.e. several individuals with a high percentage of body fat increased heat production more rapidly than others who were relatively lean. However, the fact that we never observed a heat production greater than 442 Cal/hr. is further evidence that the figure (425 Cal/hr.) is in the right range.

When heat productions on the order of 400 Cal/hr. were observed, the subjects were shivering violently and uncontrollably. It is doubtful that a greater shivering response could be evoked under any circumstances.

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